A Summary of Thermal Analysis Support to the Galileo High Gain Antenna Deployment Anomaly Recovery Effort

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ABSTRACT

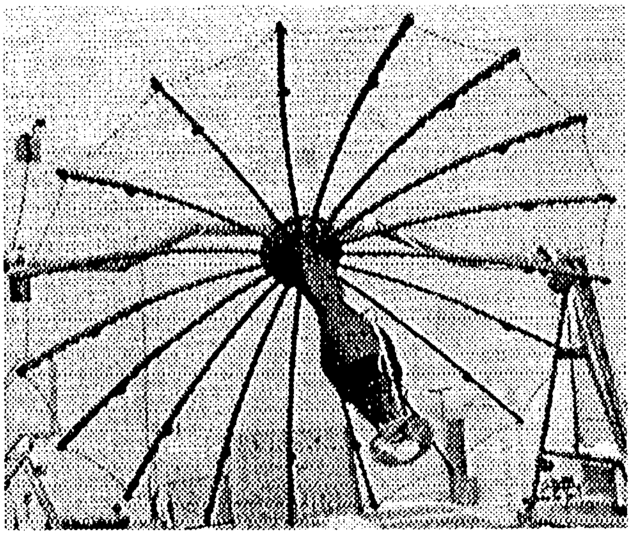

Figure 1 - Deployed high gain antenna

On April 11, 1991, the Galileo spacecraft executed a sequence of commands to unfurl its umbrella-like high gain antenna (sw Fig. 1). The initial deployment opportunity occurred at a solar distance of 1.32 AU, eight months prior to an aphelion of 2.27 AU and approximately twenty months prior to a "sling-shot" gravity-assist from the Earth which would hurl the S/C toward its ultimate destination, Jupiter. The antenna, which is based on the TDRSS antenna, was built by the Harris Corporation. It was stowed and protected from solar insolation behind a small "tip" shade during early portions of the trajectory inside 1,0 AU (see Fig. 2). Unfortunately, confirmation of deployment was not received. Immediately, a deployment anomaly team was assembled to determine likel y failure scenarios and to recommend courses of action for recovery. After intensive analysis using flight telemetry (attitude control wobble, Sun gate obscuration, and deployment motor current), the team hypothesized that a number of the antenna's 18 ribs are stuck in the stowed position, Subsequent ground testing of the spare antenna was correlated to the flight telemetry, and the team concluded that probably three ribs are stuck in their stowed postion (see Fig. 3). The power control to the deployment motors is not designed to be back-driven. Investigation of the S/C design revealed that the forces that could be applied to the antenna in order to free it were limited to: 1) spinning the S/C to induce centripetal forces; 2) stowing and redeploying nearby boom elements or repeated pulsing of the deployment motors to induce impulsive forces; 3) inducing S/C wobble; 4) firing thrusters; or 5) changing the S/C attitude relative to the Sun to promote thermally-induced forces.

In the initial assessment of possible causes, gross mechanical failures such as loss of the tip shade were quickly discounted duc to the normalcy of the thermal telemetry. The leading theory that emerged hinged on the central pins of the antenna ribs which act as braces when the ribs

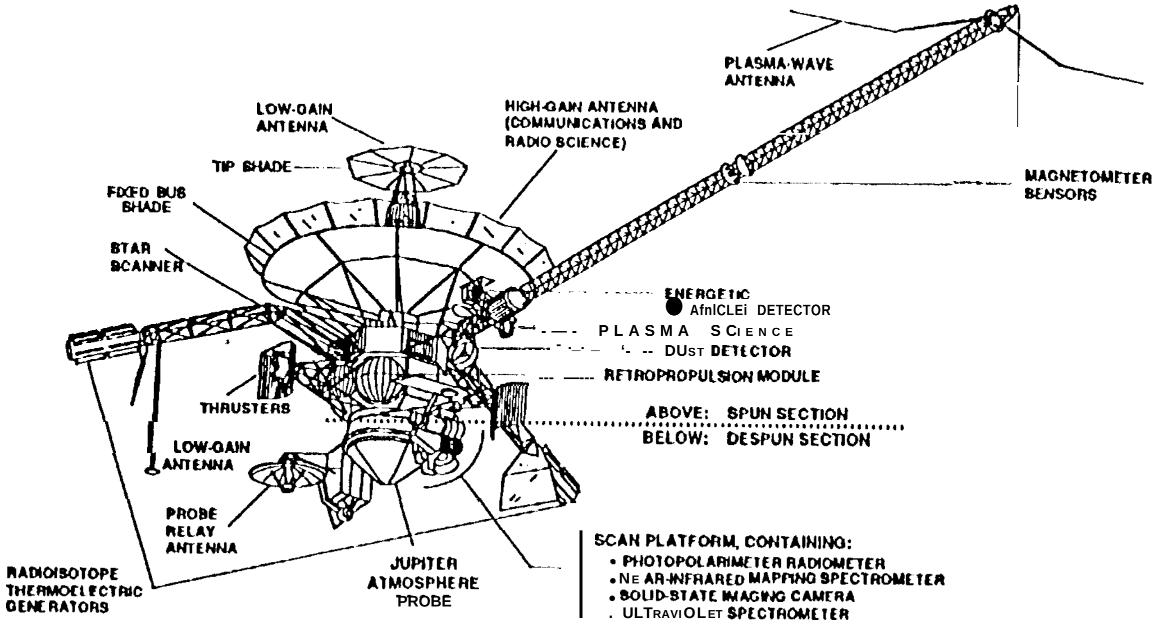

Figure 2- Galileo S/C configuration

arc stowed. It was hypothesized that a few of these ribs may be stuck due to high frictional forces with their fitting receptacle (see Fig. 4), Extreme cooling of the antenna was conjectured to be effective in creating antenna tower displacements that may free the stuck ribs. Thermal analyses were performed so that the thermally-induced contractions of the antenna tower could be quantified. In turn, these predicted contractions were utilized in structural analyses to determine if rib release might be possible, On July 10, 1992 and at a heliocentric distance of 1.84 AU, the S/C was turned 165° off the Sun to entirely shade the antenna via the fixed bus shade (see Fig 2). After 32 hours at attitude, the antenna temperatures had nearly reached steady-state values. Upon return to Sun-point, telemetry indicated that the ribs had not been freed, Furthermore, the flight temperature data suggested that the antenna temperatures were not nearly as cold as predicted. An effort was required to resolve differences between the flight data and analytical thermal model predictions, An investigative effort was undertaken to understand the details of the antenna since the antenna hardware and its thermal design were the responsibility of the Harris Corporation. In addition, the JPL analytical thermal model did not include several tower elements.

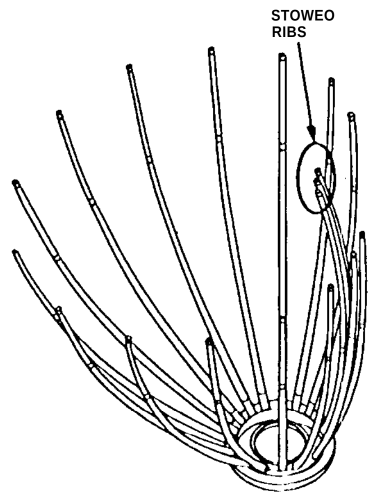

Figure 3 - Current antenna rib configuration scenario

Hence, certain heat transfer paths were either neglected or grossly approximated since their effect is minor when the antenna is heated significantly by the Sun, However, these paths are significant for the cooling attitude where the entire heat flow throughout the antenna is meager. Consequently, this model was rather deficient in satisfactorily predicting antenna component temperatures for the cooling turn attitudes. Because of the difficulty in identifying the significant heat transfer paths within the antenna for the cooling attitude, an empirical flight data correlation approach was used to incrementally refine the model to support future cooling turn activities.

A second cooling turn was performed on August 13, 1991 at a solar distance of 1.98 AU. The time at cooling attitude was increased to 50 hours. Although colder antenna temperatures were achieved, the antenna tower contraction was stil 1 short of what was believed to be necessary to free the ribs, In an effort to attain maximum cooling, a third cooling turn was performed at aphelion (2.27 AU) in December 1991. Incrementally cooler antenna temperatures were reached, but it had become increasingly evident that the required antenna tower contraction would not be attained by this cooling strategy. However, these turns provided additional flight data which could be used to correlate the antenna thermal model.

Another strategy, one which might “walk” the pins out of their receptacle by alternating cooling and heating of the antenna was proposed. Each previous cooling turn had been succeeded by a return to Sun-point, and consequent y, three thermal cycles had been implicit] y performed. In support of subsequent warming turn planning, a revision of the antenna thermal model was necessary since the initial antenna thermal model handled the ribs in a simplistic fashion, Once the thermal model was upgraded, the optimal off-Sin angle was determined to be in the vicinity of 50’. However, an optimal warming turn angle of 45° was chosen since command sequences had been previously generated for this angle, and thermal analysis results indicated that antenna tower expansion was nearly identical to the value at 50° off-Sun. As with the cooling turn analyses, work was performed to predict the thermally-induced displacements of the antenna tower. Of the three ribs that were believed to be restrained, the most optimistic scenario indicated that seven cooling and heating cycles may release all three ribs. Between January and Jul y 1992, four additional warming and cooling cycles were performed while the S/C headed toward a gravity-assist rendezvous with the Earth. Warming turn flight temperature data agreed

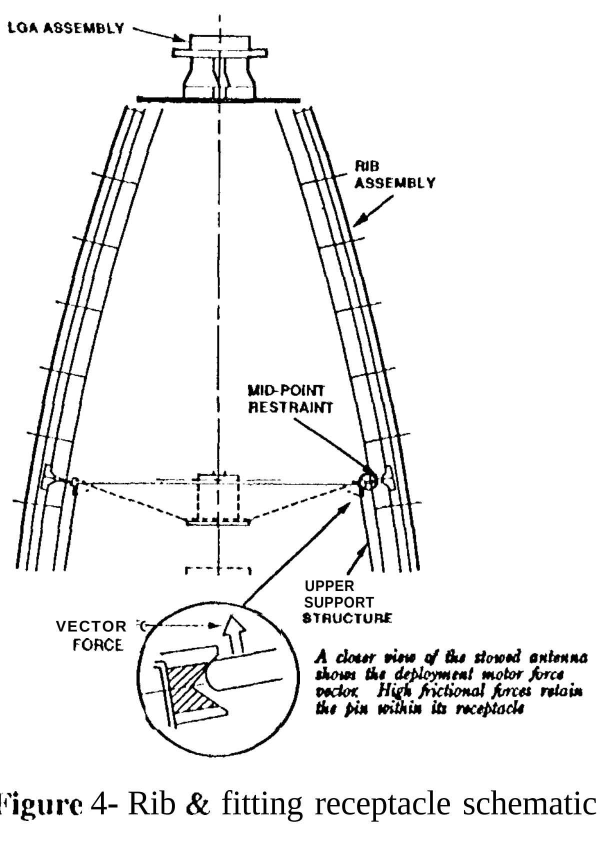

Figure 4- Rib & fitting receptacle schematic

extremely well with the analytical thermal model predictions. Unfortunately, attitude control telemetry (S/C wobble and Sun gate obscuration) indicated that the antenna had not changed from its state just after the initial deployment attempt. After seven warming and cooling cycles had been performed without any rib release, there was no longer any prospect of therms] cycling freeing the antenna.

The next approach entailed pulsing the antenna deployment motors many times to act as a hammering force. Since the motor output torque increased with temperature, the hammering was planned near the closest solar approach, approximately 1.0 AU, and at an off-Sun angle of 45°. In preparation for the hammering exercises, special activities were performed in July, September, and October of 1992 to characterize the S/C thermal response at a 45° off-Sun attitude, as well as to calibrate and characterize the antenna deployment system. In October 1992 and at a solar distance of 1.30 AU, the S/C was turned 45° off-Sun for about 48 hours and the deployment motors were pulsed on and off a few times. During late December of 1992 and January of 1993, the deployment motors were pulsed over 13,000 times while the S/C was 45° off-Sun. Although flight telemetry indicated that the antenna configuration had changed, the stuck ribs were not freed, By the end of February 1993, the deployment anomaly team was dissolved.

This paper will summarize the thermal analysis support to the efforts associated with repeated pulsing of the deployment motors and warming and cooling of the antenna to enhance thermally-induced forces. The paper will focus on the antenna-related elements, therefore there will be no discussion of the analysis for other S/C components, A summary of the initial effort to predict cooling turn temperatures will be given as well as the resolution between predictions and flight data for the first cooling turn. A discussion of the empirical correlation with the subsequent cooling turn flight data will also be presented. In addition, a discussion of the anal ytical thermal model i mprovement for the warming turn predictions and a comparison to flight data will be included. The subsequent analysis to determine the optimal off-Sun warming angle will be shown. Finally, the analysis support which focused on predicting the deployment motor temperature will be discussed including a comparison with flight data.